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Wide Field X-ray Telescope: Mission Overview

P. Rosati[1], S. Borgani[2,3], R. Gilli[4], M. Paolillo[5], P. Tozzi[6], S. Murray[7], R. Giacconi[7], A. Ptak[7], M. Weisskopf[8], W. Forman[9], C. Jones[9], and the WFXT Team

[1] ESO-European Southern Observatory, D-85748 Garching bei München, Germany
[2] Dipartimento di Fisica, Sezione di Astronomia, Università di Trieste, Via Tiepolo 11, I-34143 Trieste, Italy
[3] INFN, Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy
[4] INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
[5] Università Federico II, Dip. di Scienze Fisiche, Via Cintia, I-80126, Napoli, Italy
[6] INAF-Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34143, Trieste, Italy
[7] Department of Physics and Astronomy, The Johns Hopkins University, Baltimore MD, USA
[8] NASA Marshall Space Flight Center, Space Science Office, VP62, Huntsville, AL 35812, USA
[9] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

Abstract. The Wide Field X-Ray Telescope (WFXT) is a medium-class mission designed to be 2-orders-of-magnitude more sensitive than any previous or planned X-ray mission for large area surveys and to match in sensitivity the next generation of wide-area optical, IR and radio surveys. Using an innovative wide-field X-ray optics design, WFXT provides a field of view of 1 square degree (10 times Chandra) with an angular resolution of 5″(Half Energy Width, HEW) nearly constant over the entire field of view, and a large collecting area (up to 1 m^2 at 1 keV, > 10x Chandra) over the 0.1-7 keV band. WFXTs low-Earth orbit also minimizes the particle background. In five years of operation, WFXT will carry out three extragalactic surveys at unprecedented depth and address outstanding questions in astrophysics, cosmology and fundamental physics. In this article, we illustrate the mission concept and the connection between science requirements and mission parameters.

1. Mission concept

Exploring the high-redshift Universe, to the epochs of cluster formation all the way back to the primordial populations of galaxies and super massive black holes (SMBHs) requires sensitive, high angular resolution, wide X-ray surveys to complement deep, wide-field surveys in other wavebands. The Wide Field X-Ray Telescope (WFXT) was designed to be 2-orders-of-magnitude more sensitive than any previous or planned X-ray mission for large area surveys and to match in sensitivity the next generation of wide-area optical, IR and radio surveys. In its current concept (Murray et al. 2008) [1], WFXT is a medium-class PI mission with a broad science grasp which will build a unique astrophysical data set, consisting of $\gtrsim 5 \times 10^5$ clusters of galaxies to $z \sim 2$, $> 10^7$ AGN to $z > 6$, and $\sim 10^5$ normal and starburst galaxies at $z \lesssim 1$.

[1] http://www.wfxt.eu, http://wfxt.pha.jhu.edu

These large samples will provide a description of the cosmic evolution of baryons, map the large scale structure of the Universe, constrain and test cosmological models and fundamental physics (such as the nature of Dark Matter, Dark Energy and gravity), determine the black hole accretion history to early epochs and its intimate link with galaxy formation, and provide an unprecedented view of nearby galaxies including our own. The science breadth of WFXT is only outlined below and fully described by the specific contributions in this volume, which span a range of prominent science cases.

The high survey efficiency of WFXT, compared with other past or planned X–ray missions, is obtained by using *for the first time* a wide-field optical design, first proposed by Burrows, Burg, & Giacconi (1992). By adopting a polynomial shape of the X–ray mirros, WFXT's angular resolution is optimized over the entire 1 $\deg^2$ field of view, as opposed to the classical Wolter-I optics whose angular resolution is optimized mainly on-axis and degrades with the square of the off-axis angle (see Conconi et al. (2010), Elsner et al. (2010) and Pareschi et al. in this volume). The resulting *Grasp*= $A \cdot \Omega_{\rm eff}$ of the survey mission, i.e. the product of the telescope collecting area and the effective field of view (FoV) at the desired angular resolution, is significantly larger when compared to all other past or proposed X-ray missions, making it an unprecedented survey instrument, able to carry out *both wide and deep* surveys (see Fig.1/*left*). With such an enahanced discovery potential, WFXT will provide optimum samples for both giant ground-based telescopes for more sensitive, but narrow-field space facilities in the optical-IR and X-ray. WFXT, however, is not only a path finder for future missions, its large collecting area allows direct physical characterization of a large fraction of sources (AGN and Clusters) via X-ray spectroscopy with no need of follow-up observations. Synergy with other missions further enhances its scientic potential and breadth. WFXT is conceived for the entire astronomical community. Like the Sloan Digital Sky Survey (SDSS[2]), all WFXT data will become public through a series of annual Data Releases that will constitute a vast scientific legacy for decades.

2. Science goals and performance requirements

To define the top level mission requirements, four major science cases were identified and submitted as white papers to the Astro2010 Decadal Survey of the National Academy of Sciences: 1) Physics and Evolution of Cluster of Galaxies (Giacconi et al. 2009, Borgani et al. this volume); 2) Growth and Evolution of Supermassive Black Holes (Murray et al. 2009, Gilli et al. this volume); 3) Cosmology with Galaxy Clusters, (Borgani et al. this volume, Vikhlinin et al. 2009); 4) The very Local Universe (Ptak et al. 2009). Three extragalactic surveys, performed during five years of operation, are required to fully meet the science goals described in these papers: a *WIDE* survey covering most of the extragalactic sky ($\sim 20,000$ $\deg^2$) at $\sim$ 500 times the sensitivity, and twenty times better angular resolution than the ROSAT All Sky Survey; a *MEDIUM* survey mapping $\sim$3000 $\deg^2$ to deep Chandra and XMM sensitivity; and a *DEEP* survey probing $\sim$ 100 $\deg^2$, ($\sim$ 1000 times the area of the Chandra Deep Fields), to the deepest Chandra sensitivity, with typical sampling timescales of days to months. Survey parameters are given in Table 1. Flux limits and areas for the three surveys are shown in Fig.1/*left*, along with those of existing and planned X-ray surveys.

The capability of an X-ray observatory to carry out a survey, at a given resolution, is given by the product of the *Grasp* defined above and the time available for observation T. WFXT maximizes $A \times \Omega_{\rm eff} \times T$ through its wide-field optics design and a dedicated survey strategy which has an obvious advantage compared to general facilities, such as *Chandra* and *XMM-Newton*, which have devoted < 10% of their time to surveys. The mirror design is no more complex than a Wolter-I telescope, but yields a resolution of 5–10″

[2] http://www.sdss.org/

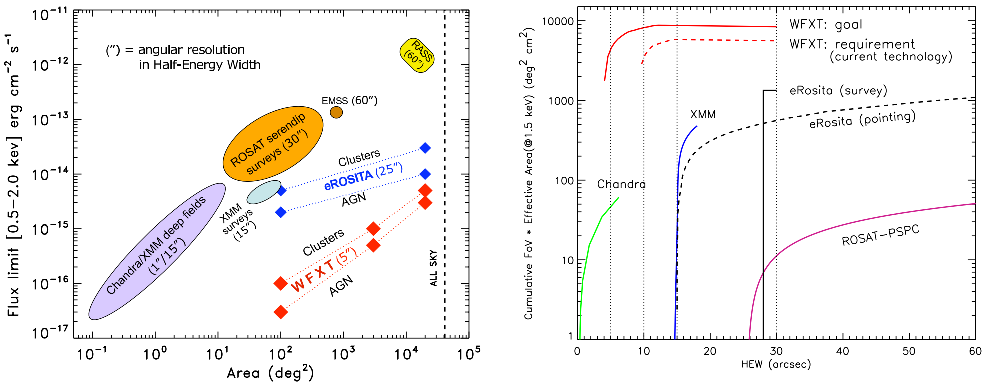

Fig. 1. *Left*: Flux limits and sky coverage for past and planned X-ray surveys. The three WFXT surveys provide an unsurpassed combination of sensitivity and sky area. *Right*: WFXT cumulative Grasp = $\Omega \times$ A, as function of angular resolution (HEW). WFXT's grasp is orders of magnitude greater than any other X-ray mission. Parameters for the planned mission *eROSITA* are taken from Cappelluti et al. in this volume.

Table 1. Description of the WFXT surveys $^{(\star)}$

Quantity	Survey		
	Deep	Medium	Wide
Ω (deg^2)	100	3000	20,000
Exposure	400 ksec	13 ksec	2 ksec
Total Time $^{(\star\star)}$	1.67 yr	1.66 yr	1.67 yr
$S_{\rm min}$(0.5 – 2 keV) point-like erg s^{-1} cm^{-2} at 5σ $^{(\star\star\star)}$	3×10^{-17} (1×10^{-16})	5×10^{-16} (1×10^{-15})	3×10^{-15} (5×10^{-15})
Total AGN detected	5×10^5	4×10^6	1×10^7
$S_{\rm min}$(0.5 – 2 keV) extended erg s^{-1} cm^{-2} at 5σ	1×10^{-16} (3×10^{-16})	1×10^{-15} (2×10^{-15})	5×10^{-15} (7×10^{-15})
Total Clusters/Groups	3×10^4	2×10^5	3×10^5

$^{(\star)}$ Values refer to goal performance parameters, those in parenthesis to minimal requirements of A_{eff} = 0.6 m^2, HEW = 10″

$^{(\star\star)}$ Total observing time assumes 76% observing efficiency

$^{(\star\star\star)}$ Flux limits in the hard 2–7 keV band are about 10 times higher

over the entire 1 deg^2 field (Pareschi et al., this volume). To demonstrate the advantage of such a mission, Fig. 1/*right* shows the cumulative field of view as a function of angular resolution for five missions, derived from their half-energy widths at different off-axis angles. Even at 10″ resolution, allowed by the wide-field design with current technology, WFXT can survey a given area to a comparable flux limit in $\sim \frac{1}{100}$ of the time that Chandra requires. For example, the simulation in Fig.3 of a single 13 Ksec observation (a *MEDIUM* survey tile) shows that WFXT would cover 1 deg^2 at the sensitivity obtained by Chandra in a total observation of 1.8 Ms of the COSMOS field (Elvis et al. 2009). The wide-field X-ray optics and mirror construction technology are also key to understand the clear advantage with respect to the upcoming *eROSITA* survey mission (Cappelluti et al., this volume) which provides a significant step forward compared to the ROSAT All-Sky Survey.

The angular resolution is a key parameter for the scientific success of such a mission. A minimum requirement of 10″ for the half-energy width is dictated by the need to improve source sensitivity, to discriminate point from extended emission, to minimize source confu-

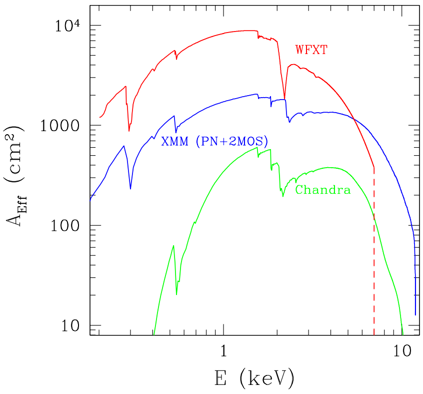

Fig. 2. WFXT collecting effective area (goal) compared with *Chandra* and *XMM-Newton* .

Table 2: WFXT Mission Performance Requirements

Parameter	*Requirement*	*Goal*
Area (1 keV)	$6,000\,cm^2$	$10,000\,cm^2$
Area (4 keV)	$2,000\,cm^2$	$3,000\,cm^2$
Field of View	1^o diameter	1.25^o diameter
Angular Resolution	$< 10''$ HEW	$\leq 5''$ HEW
Energy Band	0.2 - 5 keV	0.1 - 7 keV
Energy Resolution	$\frac{E}{\Delta E} > 10$	$\frac{E}{\Delta E} > 20$
Time Resolution	$<$ 3 seconds	$<$ 1 second
Orbit	550 km cir., $< 6^\circ$ incl.	
Mission Lifetime	5 years	

sion and to allow an efficient identification of optical counterparts. The latter is an essential process for the work-flow of any science case. While a commonly used figure of merit for the *discovery potential* of a survey mission is the *Grasp*, a more appropriate figure of merit in X-ray surveys for the *discovery speed*, i.e. the ability to *discover and identify* sources should scale as $A\Omega T \times \mathrm{HEW}^{-2}$, since the number of possible counterparts scale with the area of the error circle. For deep observations, no longer signal limited, the dependence on the angular resolution will be even faster (up to HEW^{-3} in the background limited regime). Specifically, a $10''$ HEW yields a 1.5–2$''$positional accuracy thus easing the identification of millions of sources, a daunting task with resolutions exceeding $10''$. While $10''$ is feasible with present technology (Pareschi et al. this volume), a goal of HEW$\approx 5''$approximately constant across the FoV has been chosen. This will *i)* further increase the sensitivity for point and extended sources (e.g. groups), *ii)* enable AGN/cluster discernment at any redshift, *iii)* enable confusion-free deep imaging, *iv)* provide *Chandra*-like positional accuracy ($\lesssim 1''$) with a source identification success rate of $>$ 90% (Brusa et al. this volume), *v)* resolve cool cores of $z \gtrsim 1$ clusters (Santos et al. 2010) (essential for cosmological applications, see Borgani et al. this volume), and *vi)* allow the detection of sharp features (shocks, cold fronts, cavities) in the intra-cluster medium (ICM).

The required effective area of the telescope at 1 kev is 0.6 m^2, with a goal of up to 1 m^2, to still fit within the mass budget and costs of a medium class mission with current or forseeen technology. This large collecting area ultimately enables wide surveys at unprecedented depth (Fig.1) within the 5 year life time of the mission, and thus allows very large volumes of the Universe to be explored to large redshifts. In turn, this *i)* allows one to trace the X-ray luminosity function of clusters and AGN (and underlying mass functions of clusters and SMBHs) over a wide range of masses and redshifts, and *ii)* enables physical characterization of large samples of sources via their spectral analysis (see Borgani et al. and Gilli et al. in this volume for predictions of expected number of clusters and AGN and a detailed discussion of related science cases). As shown in Fig.2, it is also important to note that the current (goal) design delivers an effective area as large as the one of *XMM* at 5 keV, this provides a significant benefit when measuring temperatures and redshifts (using the Fe K line) from the spectral fits of clusters as well as the detection of large populations of obscured AGN (see Tozzi et al. in this volume).

The $A\Omega$ and angular resolution combination also translates in very interesting WFXT capabilities in the *time domain*, enabling short

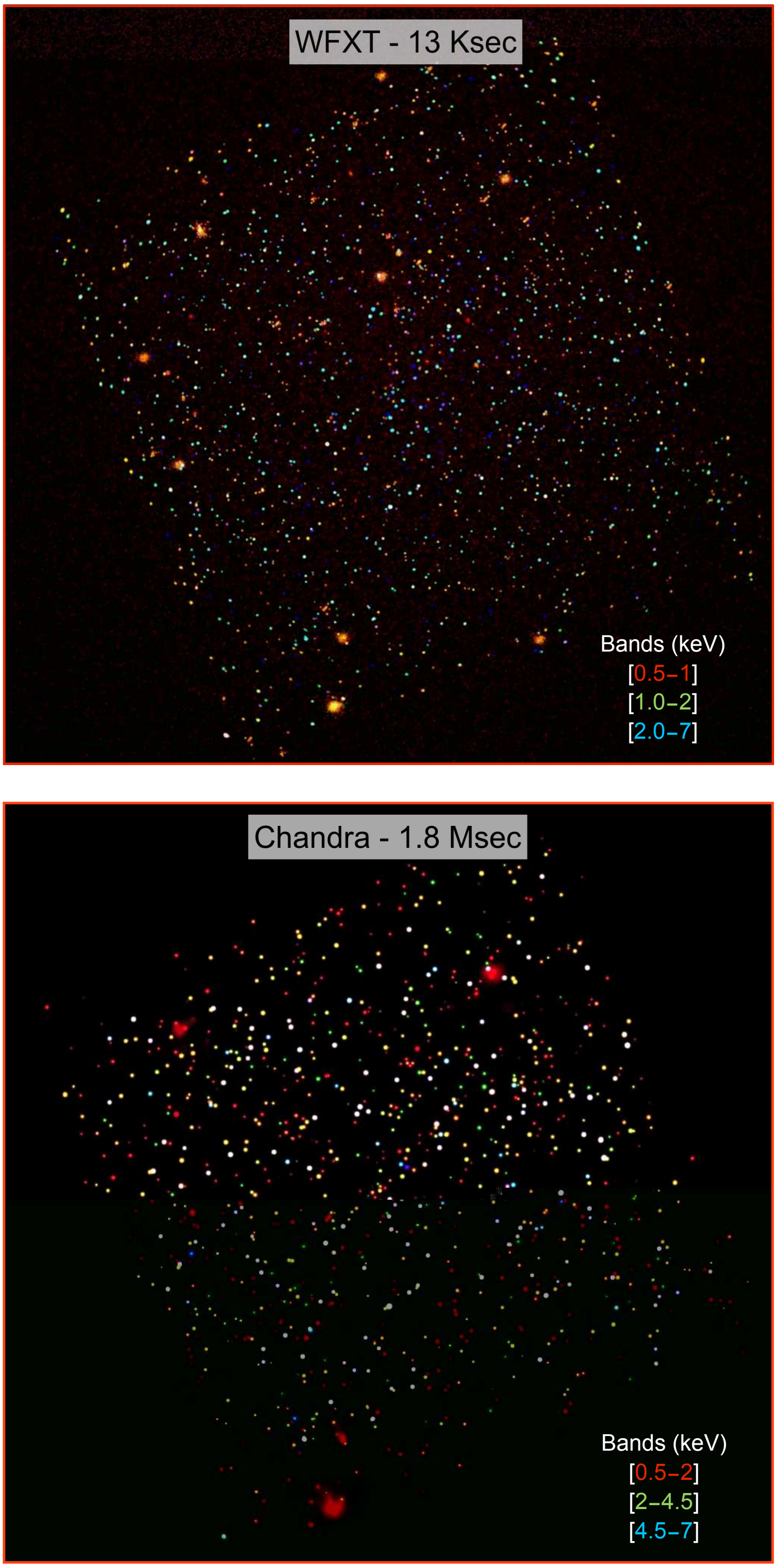

Fig. 3. Simulated WFXT image of the COSMOS field (top) observed with Chandra over 1 deg^2 (bottom) (Elvis et al. 2009). The flux limit of the two images is similar ($\sim 5 \times 10^{-16}$ erg s^{-1}cm^{-2} in 0.5-2 keV). However the WFXT image (1 deg^2) is obtained with a single 13 ksec exposure (as part of the Medium survey), with an angular resolution (5″ HEW) close to Chandra's average ($\sim$ 3″). The WFXT simulation was constructed from the Chandra COSMOS catalog Elvis et al. (2009) with methods described in Tozzi et al. (this volume). Bluer sources emit harder X-rays in the 0.5–7 keV band.

Table 3. WFXT Science and Performance Requirements

Performance Requirement	*Observational/Science Requirements*
PSF HEW <10″(goal of 5″) across FoV	*(i)* Sensitivity for point and extended sources *(ii)* Minimize source confusion *(iii)* Discriminate extended sources from AGN at $z > 1$ *(iv)* Resolve cluster cool cores (50–100 kpc) at any redshift (10″ corresponds to 80 kpc at $z = 1$) *(v)* efficient identification of optical counterparts
Large grasp = FoV×A_{Eff} FoV ≥ 1 deg^2 0.6(0.2) < A_{Eff} < 1(0.3) m^2 at 1(4) keV	High survey efficiency and vast discovery space: *(a)* to detect large numbers of sources thus measuring luminosity functions over a wide range of masses/luminosities and redshifts; *(b)* to guarantee high S/N spectra for significant subsets thus enabling physical characterization of clusters and AGN, including redshift measurements (with X-ray spectroscopy, without the need of follow-up observations); *(c)* to detect and characterize large number of variable and transient sources (AGN, GRB, SNe etc.)
Low particle background achieved by low Earth orbit	*(i)* Improved limiting flux for point/extended sources; clusters out to large redshifts (proto-clusters at $z \sim 2$); *(ii)* Detect low surface brightness diffuse emission for nearby galaxies and clusters (out to and beyond the virial radius)
Spectral resolution ($10 < E/\Delta E < 20$)	*(i)* Detect the Fe-K emission in clusters and AGN; *(ii)* Spectral characterization of clusters, AGN and galaxies

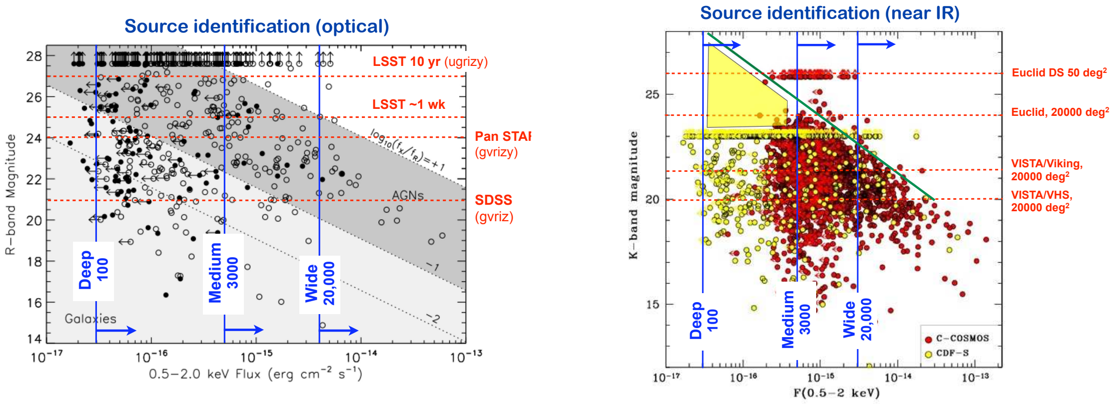

Fig. 4. Source identification strategy for WFXT X-ray sources in the Optical and near-IR based on the distributions of flux ratios from *Chandra* deep surveys in the R-band (Luo et al. 2008) and K_{AB}-band (courtesy of C.Vignali). Current and planned future wide-area surveys are indicated at different magnitude limits.

temporal sampling observations and simultaneous monitoring of large sky areas, which will allow one to detect and study variable and transient X-ray populations of galactic and extragalactic sources (see Paolillo et al. this volume).

In addition, WFXT's low-Earth orbit reduces the particle background to take full advantage of the instrument sensitivity and high-quality PSF. This is important for the detection and spectral analysis of low-surface brightness features such as distant groups, the most dis-

tant clusters and the outskirts of nearby clusters (Ettori& Molendi, this volume).

We summarize in Table 2 the performance requirements and goals of the mission, and in Table 3 how these parameters are connected to the observational and science requirements.

3. Synergies with other surveys

While we have emphasized how several science objectives can be achieved with the WFXT data only using the X-ray spectral analysis of significant sub-samples of sources with sufficient signal-to-noise, there is no doubt that the synergy of WFXT with the next generation of multi-wavelength deep wide-area surveys will greatly expand the scientific grasp of the mission and will consolidate its vast legacy value for decades.

The multi-wavelength properties of more than 10^7 sources will be available from the combination of current and future wide-area surveys, such as Pan-STARRS[3] and LSST[4] in the optical bands, and in the near-IR surveys (VISTA, WISE, and JDEM/Euclid possibly by the end of the decade), which will allow their identifcation and a measurement of their photometric redshifts. Obtaining deep imaging in the near-IR over the entire extra-galactic sky to identify the most obscured (and most distant) AGN and distant clusters will remain the main challenge, a task which only space-based surveys at $1-2\,\mu m$, such as those proposed for the Euclid[5] or JDEM[6] missions, can perform. We illustrate in Fig.4 the identification strategies of AGN for the three WFXT surveys, based on their optical/nearIR-to-X-ray flux ratios measured in deep *Chandra* surveys. The extension of the multi-wavelength coverage to longer wavelengths, in the submm (CCAT[7]) and radio with SKA[8] (see Padovani, this volume), will complete the information on the spectral energy distribution of different source populations with crucial implications on our understanding of their physics and evolution.

For example, WFXT observations of thousands of clusters will provide redshifts and detailed physical insights, such as temperature and entropy profiles, metallicity of the ICM, mass density profiles of gas and dark matter (DM). By combining this information with optical and near-IR photometry of the cluster galaxies and with future high sensitivity Sunyaev-Zeldovich surveys, one will be able to obtain a comprehensive picture of the evolution of the baryons in their hot and cold phases and how star formation and AGN activity affects the physics of the ICM. By combining these data with lensing studies carried out with ground (e.g. LSST) and space (e.g. Euclid) observations, one will obtain detailed DM mass density profiles on a range of redshifts and masses which can be compared with current structure formation models thus setting strong constraints on the foundations of the ΛCDM paradigm.

The spectroscopic follow-up study of large subsamples of WFXT sources will remain a serious challenge. Dedicated wide-field, high-multiplexing spectrographs on 8m class telescopes currently under study will be suitable for a wide range of science cases. The systematic spectroscopic identification work in large ($\sim 10^4$ deg^2) survey areas can partly be carried out with near-IR slitless surveys, which are part of the Euclid/JDEM mission concepts. A more effective approach to the study of a large variety of sources over a wide redshift range would require wide-area *slit*-spectroscopy from space, such as the one proposed for the SPACE(Cimatti et al. 2009) mission.

Moreover, in combination with more sensitive, narrow-field observatories, WFXT will be an outstanding source of interesting high redshift clusters and AGN for follow-up studies with JWST (or its successors), ALMA, the next generation of giant (30-40m) ground-based telescopes, and X-ray observatories (i.e., IXO and Gen-X).

[3] http://pan-starrs.ifa.hawaii.edu/public/home.html
[4] http://www.lsst.org
[5] http://sci.esa.int/euclid
[6] http://jdem.gsfc.nasa.gov/
[7] http://www.submm.org/
[8] http://www.skatelescope.org/

4. Conclusions

In this article, we have illustrated the concept of the WFXT mission and how the mission requirements flow from the main science drivers and observational requiremens. We refer the reader to all the contributions in this volume for a detailed discussion of several science cases, which range from the formation and evolution of SMBHs and clusters to stellar populations and compact objects in the Galaxy; from Cosmology to the physics of clusters and AGN, including the study of early-type and star-forming galaxies. This collection of science cases is by no means complete, but can be considered the basis on which the scientific potential of WFXT can be further explored as the technological development continues. It is important to emphasize that the gain margin of WFXT compared to previous or planned X-ray missions in conducting surveys is so large that its scientific impact would remain very strong even if cost or technological challenges will drive a redefinition of its performance parameters. In the suite of requirements under study, as explained above, the angular resolution remains the one parameter on which is very difficult to compromise, as *Chandra* observations have unambigously and definitively taught us.

When examining the range of wide-area high-sensitivity surveys being planned for this decade, in the optical, IR, submm and radio regimes, WFXT stands out as the only one which will be able to match these surveys in coverage, sensitivity and angular resolution at soft X-ray wavelengths. Coordinated surveys from X-ray to radio wavelengths, which have been carried out in small areas of the sky ($\lesssim$ 1 deg^2) over the last decade, have definitively established the crucial value of the multi-wavelength approach in astrophysics which has fueled phenomenal progress in many areas. X-ray observations have been key to such a progress as they have the unique ability to probe phenomena and unveil sources powered by *gravity*. On the other hand, systematic wide-area surveys have demonstrated that they are able to produce major discoveries and address fundamental questions, as also underscored by their high level of high-impact publications (Madrid & Macchetto 2009). We therefore argue that the lack of a mission like WFXT in the suite of future multi-wavelength wide-area surveys will ultimately limit their scientific potential.

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